UNIVERSITI PUTRA MALAYSIA

PERFORMANCE AND EMISSION EVALUATION OF A SINGLE CYLINDER DIESEL ENGINE RUNNING ON PALM OIL METHYL ESTER ENRICHED WITH METHYL OLEATE

MOHAMAD A. HASAN ALTAIE

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By

MOHAMAD A. HASAN ALTAIE

Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia, in Fulfillment of the Requirements for the Degree of Doctor of Philosophy

December 2016

DEDICATION

This work is dedicated to spirit of my father

Mr. Ahmed Hasan Altaie

Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfillment of the requirement for the degree of Doctor of Philosophy

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Chairman : Associate Prof. Rimfiel B. Janius, PhD
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Biodiesel is a renewable, alternative diesel fuel derived from various oils or fats through transesterification. Biodiesel consists of alkyl esters of the parent oil. Palm oil methyl ester (PME) is a prominent biodiesel in Southeast Asian countries, such as Malaysia and Indonesia, which have a surplus production of palm oil. However, the methyl ester exhibits poor cold flow characteristics because of the substantial amount of saturated fatty acids in palm oil. By contrast, methyl oleate (MO) possesses excellent cold flow properties because of its highly unsaturated components. MO can be produced from low-cost raw materials that generally contain high amounts of oleic acid.

In this study, various blends were prepared through enrichment of PME with MO under different volumetric ratios of PME80:MO20, PME70:MO30, PME60:MO40, and PME50:MO50 (vol/vol, %). The optimum blend with improved cold flow properties than neat PME was determined. The physicochemical properties of the PME-MO blends were also investigated and compared with those of neat PME.

The cloud point, cold filter plugging point, and pour point of the blends significantly improved compared with those of the neat PME. The increasing enrichment proportion of MO in the PME-MO blends until 50% (vol/ vol, %) led to 70.38%, 91.69%, and 100% improvement in cloud point, cold filter plugging point, and pour point values, respectively, compared with those of the neat PME. Important fuel properties (i.e., cetane number, kinematic viscosity, density, gross heating value, net heating value, flash point, and acid value) were also examined. Furthermore, the oxidation stability of the PME-MO blends was assessed 5 months after blend preparation. All fuel properties of the blends were within the specified permissible limits of biodiesel standard

(ASTM D 6751) and very stable; as such, the mixtures did not show rapid decrease in oxidation stability.

The PME-MO blends that met the specifications of ASTM D 6751 were submitted for further investigation to determine the performance and exhuast emissions in a single-cylinder direct-injection diesel engine.. The parameters associated with engine performance included torque, brake power, brake specific fuel consumption, and brake thermal efficiency. The PME-MO blends yielded lower torques and higher brake specific fuel consumptions than petroleum diesel because of the lower calorific value of biodiesel. Moreover, the blends showed significantly reduced carbon monoxide (CO) and hydrocarbon (HC) emissions and exhaust gas temperatures (EGT). Increasing the MO proportion up to 50% (vol/vol, %) reduced CO, HC, and EGT to 71.50%, 37%, and 5%, respectively, which were lower than those of petroleum diesel.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk ijazah Doktor Falsafah

PENILAIAN PRESTASI DAN EMISI ENJIN SATU SILINDER YANG DIKUASAI OLEH METIL ESTER KELAPA SAWIT YANG DIPERKAYAI DENGAN METIL OLEATE

Oleh

MOHAMAD A. HASAN ALTAIE

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Biodiesel ialah satu bahan bakar alternatif boleh dipebaharui yang diterbitkan daripada pelbagai jenis minyak atau lemak melalui transesterifikasi. Biasanya biodiesel mengandungi alkil ester minyak induk. Metil ester minyak sawit (PME) ialah satu biodiesel terkemuka di negara Asia Tenggara seperti Malaysia dan Indonesia, yang mempunyai pengeluaran minyak sawit lebihan. Walau bagaimana pun, disebabkan kandungan asid lemak tepu yang tinggi dalam minyak sawit, metil ester yang terhasil mempunyai ciri-ciri aliran dingin yang tidak baik. Sebagai perbandingan, metil oleate (MO) menunjukkkan sifat aliran dingin yang cemerlang disebabkan komponennya yang amat tak tepu. MO boleh dihasilkan daripada bahan mentah kos rendah yang amnya mengandungi asid oleik yang tinggi. Dalam kajian ini, berbagai campuran disediakan melalui pengayaan PME dengan MO dengan nisbah isipadu yang berlainan. Nisbah isipadu campuran PME-MO adalah: PME80/MO20, PME70/MO30, PME60/MO40, dan PME50/MO50 (vol/vol, %). Objektifnya adalah untuk menentukan campuran optimum yang boleh memberi sifat aliran dingin yang lebih baik daripada PME tulin dan untuk mengkaji penggunaan campuran PME-MO (biodiesel) dalam enjin diesel satu silinder, suntikan terus. Sifat fizikal-kimia campuran PME-MO diselidiki dan dibandingkan dengan sifat PME tulin. Titik keruh, titik dingin penyumbatan penapis, dan titik tuang bagi PME-MO menunjukkan penambahbaikan yang signifikan berbanding nilai-nilai PME tulin. Peningkatan nisbah MO dalam PME-MO sehingga 50% (vol/vol, %) telah membawa kepada pengurangan 70.38%, 91.69%, dan 100% masing-masing dalam titik keruh, titik dingin penyumbatan penapis, dan titik tuang dibandingkan dengan nilai-nilai PME tulin. Sifat-sifat penting bahan bakar (iaitu nombor setana (CN), kelikatan kinematik, ketumpatan, nilai penghabaan kasar, nilai penghabaab bersih, titik nyala, kestabilan pengoksidaan, dan nilai asid) juga disiasat. Semua sifat bahan bakar bagi PME-MO didapati berada dalam had bolehterima tertentu piawai biodiesel (ASTM D6751).

Pengaruh sifat dan struktur sebatian PME dan campuran PME-MO ke atas prestasi dan pelawasan enjin dibandingkan dengan nilai-nilai diesel petroleum pada keadaan beban penuh. Hasil ujikaji menunjukkan bahawa kedua-dua PME dan campuran PME-MO mengeluarkan kilas yang lebih rendah dan penggunaan bahan bakar tertentu brek yang lebih tinggi disebabkan oleh nilai kalori yang lebih rendah. Pengurangan dalam pelawasan karbon monoksida (CO) dan hidrokarbon (HC) serta pengurangan dalam suhu gas ekzos (EGT) bagi biodiesel yang diuji juga didapati.

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I certify that a Thesis Examination Committee has met on 22 December 2016 to conduct the final examination of Mohamad A. Hasan Altaie on his thesis entitled "Performance and Emission Evaluation of a Single Cylinder Diesel Engine Running on Palm Oil Methyl Ester Enriched with Methyl Oleate" in accordance with the Universities and University Colleges Act 1971 and the Constitution of the Universiti Putra Malaysia [P.U.(A) 106] 15 March 1998. The Committee recommends that the student be awarded the Doctor of Philosophy.

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This is to confirm that:

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LIST OF ABBREVIATIONS

ASTM	American Standards Testing Method
AV	Acid value
B100	100% Biodiesel
B5	5% Biodiesel 95% pure diesel fuel
B20	20% Biodiesel 80% pure diesel fuel
B30	30% Biodiesel 70% pure diesel fuel
BSFC	Brake specific fuel consumption
BP	Brake power
BTE	Brake thermal effeciency
CFI	Cold flow improver
CFPP	Cold filter plugging point
CH_3OH	Methanol
CIE	Compression ignition engine
CN	Cetane number
CO	Carbon monoxide
CP	Cloud point
D	Density
DSC	Defferential scanning Calorimetry
EGT	Exhaust gas temperature
FA	Fatty acid
FAME	Fatty acid methyl ester
FFA	Free fatty acid
FP	Flash point
GCMS	Gas chromatography mass spectrum
GHV	Gross heating value
Ha	Hectare
HC	Hydrocarbon
ICN	Individual cetane number
KOH	Potassium hydroxide
KV	Kinematic viscosity
kW	Kilowatt
MJ	Mega joule
MO	Methyl oleate
MP	Melting point
MPOB	Malaysian Palm Oil Board
MW	Melocualr weight
NHV	Net heating value
NaOH	Sodium hydroxide
Nm	Newton meter
Nox	Nitrogen oxide
OX	Oxidation satbility
P80:O20	80% palm oil methyl ester 20% methyl oleate
P70:O30	70% palm oil methyl ester 30% methyl oleate
P60:O40	60% palm oil methyl ester 40% methyl oleate
P50:O50	50% palm oil methyl ester 50% methyl oleate
PME	Palm oil methyl ester
PORIM	Palm Oil Research Institute Malaysia

PP	Pour point
R^2	Coefficiency of determination
rpm	Revolution per minute
SAE	Society of Automotive Engineers
T	Torque
ULSD	Ultra-low sulfur diesel
WC	Water content

CHAPTER 1

INTRODUCTION

1.1 Background of research

With increasing global energy crises and environmental awareness, biodiesel fuel has been increasingly used as alternative energy source because of its environmental advantages. Biodiesel fuel is derived from various feedstock sources, such as edible or non-edible vegetable oils, animal fats, and used cooking oil. Homogeneous-based catalyst is widely applied in oil and fat transesterification, wherein methanol is preferred among other short-chain alcohols (Serrano et al., 2014). Biodiesel fuel is safe to handle, biodegradable, contains no sulfur, non-toxic, and has higher cetane number (CN) than diesel (Aransiola et al., 2014; Singh & Singh., 2010). Biodiesel is commonly blended with diesel fuel, such as B20. Biodiesel–diesel blends of up to 5 (vol%, vol%) (B5) are permitted according to the diesel fuel standard ASTM D975, whereas the standard of ASTM D7467 is specific to biodiesel–diesel blends from B6 to B20. Pure biodiesel (B100) should meet ASTM D6751 specifications for commercial use. In the European Union, the standard EN 14214 is specific to neat biodiesel, and the EN 590 standard is employed for petroleum diesel until B5 (Perez & Casas, 2010).

Rapeseed, soybean, sunflower, palm oil, cottonseed, and peanut are predominant feedstock sources for biodiesel production (Gunstone, 2009). About 45 million tons of palm oil is produced worldwide; the highest producer is South East Asia, contributing 89% of the total palm oil production (40% from Malaysia, 46% from Indonesia, and 3% from Thailand). In Malaysia, a total of 4.5 million hectares of land is utilized for cultivation of oil palm and the amount of palm oil produced reached 18.562 million tons in 2016. Moreover, oil palm is the major feedstock for biodiesel in tropical regions and considered the highest yielding oil crop, producing approximately 4–5 tons/ha oil annually, which is 10 times higher than that of soybean (Ong et al., 2011). In 2006, the Malaysian Government approved the use of about 40% (approximately 6 million tons) of the total palm oil produced (15.8 million tons) for biodiesel manufacture (Mofijur et al., 2013).

1.2 Problem statement

Biodiesel exhibits poor cold flow properties under low-temperature conditions compared with conventional diesel fuel, thereby restricting their use as fuel. The cold flow performance of biodiesel can be characterized by cloud point, pour point, cold filter plugging point, and viscosity (Drapcho et al., 2009).

The cold flow properties of biodiesel are affected by the concentration of highly saturated methyl esters (i.e., methyl palmitate [C16:0] and methyl stearate [C18:0]). For example, tallow biodiesel contains 25–37 wt% methyl palmitate and 9.5–34.2 wt% methyl stearate. Saturated methyl esters C16:0 and C18:0 exhibit high melting points of 30 °C and 39.1 °C, respectively, and increased average cloud point and pour point values of 14 °C and 13 °C, respectively. Biodiesel with low saturated methyl ester content tends to have favorable cold flow properties. Methyl oleate (MO, C18:1) possesses a melting point of −20 °C, indicating that unsaturated esters have lower melting points than the corresponding saturated esters and the melting point decreases with increasing unsaturation degree. Thus, biodiesel with relatively high unsaturated esters tend to have lower cloud point and pour point values; examples of this type of biodiesel include rapeseed oil biodiesel and low palmitic soybean oil biodiesel (Konthe et al., 2010). Biodiesel with high saturated esters causes diesel engine operation problems at low temperatures because temperature adversely affects flow properties. Crystallization of saturated esters during cold seasons induces fuel starvation and operability issues associated with solidified material that partially or totally clogs fuel lines and filters, resulting in poor engine fueling (Barabas & Todorut, 2011). However, the existing fuel standard ASTM D6751 does not contain explicit specifications regarding the cold flow properties of fuel.

Palm oil biodiesel contains high amounts of saturated esters (C16 and C18), leading to poor cold flow properties. Palm oil biodiesel also possesses up to 48 wt% saturated esters and increased cloud point and pour point values of 17 °C and 13 °C, respectively (Konthe et al., 2010). Moreover, palm oil exhibits poor cold flow properties at low temperatures, thereby restricting their use as biodiesel (Verma et al., 2016; Lv et al., 2013; Zuleta et al., 2012; Sandra et al., 2013). Lin et al. (2009) tested eight types of biodiesel to determine the effect of fuels on DI engine; the highest brake specific fuel consumption was observed in palm oil methyl ester (PME), which contains approximately 50% saturated esters and exhibits low volumetric calorific value. This finding indicates that complete combustion can be obtained at low temperatures. As such, the increase in BSFC is higher when using PME than when using other kinds of biodiesel fuel.

Various approaches have been developed to improve the cold flow properties of biodiesel. Blending a small quantity of biodiesel (up to 20%) with petroleum diesel can significantly improve cold flow properties, but high blending ratios negatively affect fuel properties (Ali et al., 2016). In this regard, additives are used to enhance pour point of fuel (Bhale et al., 2009; Soriano et al., 2006). However, this cold flow additive approach may lead to issues associated with additive compatibility and unintended effects on other fuel properties because most additives are designed for petrodiesel only (Knothe, 2009). Fractionation method is employed to decrease the amount of saturated compounds and improve cold flow properties. This process increases the cost per unit mass and significantly decreases the total product yield (Knothe et al., 2010). Blending biodiesel from different sources is an effective, economical, and widely used approach to reduce the cold flow properties of biodiesel (Knothe et al., 2010; Park et al., 2008; Zuleta et al., 2012; Rashid et al., 2012). Blending fatty acid methyl esters (FAMEs) from highly saturated raw materials with other FAMEs with low saturated content can improve the cold flow performance.

MO can be produced from various low-cost sources (Burdett et al., 2005; Cardoso et al., 2008). Wang et al. (2007) mentioned that the fatty acid composition of feedstock can be modified. Raw materials which are mostly monounsaturated compound (i.e., oleic) enhances the equilibrium tradeoff between cold flow property and oxidation stability. In contrast to raw materials, which are mostly polyunsaturated fatty acids compounds (i.e., linoleic and/or linolenic) do not enhance the equilibrium tradeoff between cold flow property and oxidation stability due to their reduced oxidation stability (<1 h). Moreover, polyunsaturated fatty acids (i.e., linoleic and linolenic) are more susceptible to oxidation than other saturated or monounsaturated components. Monounsaturated fatty acids possess oxidation rates 10 times higher than linoleic fatty acids and even 15 times higher at 20 °C until 100 °C (Cankci et al., 1999). Ramli and Siew (2009) reported that oil manufacturers worldwide started to produce oils with high oleic contents several years ago. The increased global demand for high oleic oils resulted in the expansion of high oleic crop cultivation in Europe.

Leung et al. (2005) investigated the stability of high oleic rapeseed biodiesel with 62% monounsaturated content stored either exposed or not exposed to air and daylight conditions for 52 weeks; samples stored at 4 °C and 20 °C degraded by less than 10% within 52 weeks.

1.3 Objectives of study

This research proposes a novel method for PME enrichment with MO. The extent of PME enrichment with MO was investigated to determine the optimal blend with the lowest cold flow properties that satisfy the ASTM D6751 biodiesel standard.

The specific research objectives are as follows:

1- To investigate the impact of enriching PME with various MO proportions on the cold-flow and fuel properties of the resulting PME-MO blends.

2- To compare the performance and the exhaust emissions generated of a single-cylinder diesel engine running on petroluem diesel fuel, PME and PME-MO blends.

3- To determine the relationship between concentrations of pollutant (i.e. CO, HC, NOx) as well as EGT in a diesel engine exhaust and the unsaturated degree of investigated biodiesel tested.

1.4 Scope and limitation of study

MO is the unsaturated methyl ester used to enrich PME. All physical and chemical properties of PME and the resulting PME–MO blends were tested and compared with the specification of ASTM D6751. Fuel additives, engine combustion characteristics, durability effect on the engine using biodiesel fuel, economics of fuel and biodiesel–diesel blends were out of the scope of the present work. The major limitation of this study is the unavailability of multiple cylinder compression ignition engines for testing of engine performance. A naturally aspirated single-cylinder diesel engine was employed to assess the performance of engine and exhaust emissions as opposed to the widely used multiple cylinder compression ignition engines. Consequently, the results may not be generalized to all compression ignition engines because performance characteristics differ between a single cylinder engine and a multi-cylinder engine. High number of cylinders will use large amounts of fuel to produce the same amount of power.

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